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(54) Geophysical exploration system.

(57) A system is provided for collecting and interpreting data indicative of the condition of a geological structure. The system comprises a plurality of geophone sensors (221), in the form of structural moment detectors, and electronic circuitry (222) for processing and manipulating signals derived from the sensors (221). In use the sensors (221) are fixed in position such as to preferentially detect seismic disturbances in pre-selected directions. In one embodiment, at least some of the electronic circuitry (222) associated with each geophone sensor sensor (221) is provided in the same housing as the sensor to form a unitary device termed a structural information detector.

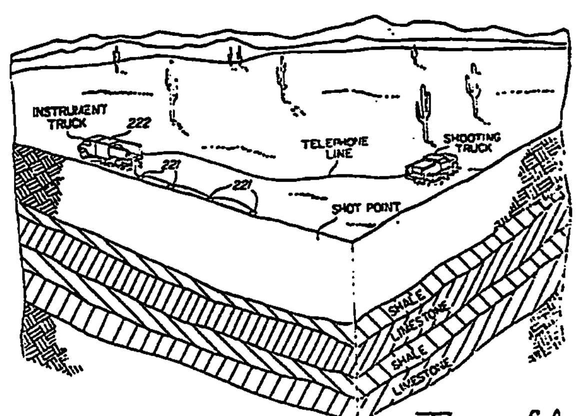

FIG-5A

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GEOPHYSICAL EXPLORATION SYSTEM

This invention relates to a geophysical exploration system employing structural moment detectors.

Structural moment detectors or flexural rigidity sensors are known which are constituted by optical sensors in the form of autocollimators insensitive to linear dynamic motion but responsive to angular deflection of one end of the sensor with respect to the other. For example, such sensors are disclosed in the patent to Rossire, U.S. No. 3,229,511 and in the publication entitled "The Structural Rigidity Sensor: Applications in Non-Destructive Testing", published by the Air Force Systems Command, United States Air Force (Frank J. Seiler Research Laboratory, Publication SRL-TR-75-0017, October 1975). See also the U.S. patents to Okubo Nos. 4,159,422 issued June 26, 1979 and 4,164,149 issued August 14, 1979.

Systems which employ structural moment detectors to measure and record certain effects of forces acting on a structure are also disclosed in the publications described above. For example, the Rossire patent discloses an aircraft attitude control system in which a structural moment detector is used to sense wing loading and automatically adjust the attitude of the aircraft to maintain wing loading within safe operational limits.

It is an object of the present invention to provide systems employing structural moment detectors and application to geophysical exploration.

Accordingly, the present invention provides a geophysical exploration system, characterised in that it comprises, in combination:

a) a plurality of structural-moment-detector geophone sensors mounted on a geological structure such as to preferentially detect seismic disturbances in pre-selected directions

and output corresponding electrical signals.

b) processing means for processing said output signals to modify the information content thereof, including rejecting any components of said signals indicative of the effects of seismic disturbances other than in said pre-selected directions; and

c) signal-manipulating means for manipulating the processed signals output by the processing means to provide secondary signals indicative of the condition of said geological structure.

The systems of the invention can employ substantially conventional structural moment detectors, the output of which is simply raw data which does not directly indicate or give useful information concerning the effect of forces acting on a structure to which the sensor is attached. In such cases, the raw data from the sensors is conditioned and processed by external electronics, including microprocessors and computational software, usually necessarily located at locations remote from the sensors, themselves.

Alternatively the systems of the invention can employ structural information detectors in which the raw signal from the optical sensor of an optical structure moment detector is converted and processed within a unitary device (either a single-piece device or a multi-component device in which each of the components is assembled to form an integral unit) such that the electrical signal output of the device has a directly useful information content which can be displayed or recorded by any conventional means or which can be directly utilized to activate control systems.

The term "surface coordinate vector" as used herein is intended to means both the normal and the tangent to the surface of a structure and any angle

therebetween.

The invention will now be particularly described, by way of example, with reference to the accompanying diagrammatic drawings, in which:

Fig. 1 is a sectional view of a typical prior art structural moment detector;

Fig. 2 is a typical schematic of the LED driver circuit of the structural moment detector of Fig. 1;

Fig. 3 is a typical schematic of the readout electronics circuits of the structural moment detector of Fig. 1;

Fig. 4 is a schematic drawing of a monitoring system embodying the invention;

Fig. 5A is a schematic perspective view illustrating the use of the monitoring system of Fig. 4 to make geophysical measurements;

Fig. 5B shows a typical chart trace output by the Figure 5 arrangement;

Fig. 6 is a generalised block diagram illustrating the major sub-components of a structural information detector suitable for use in the systems of Figures 4 and 5;

Fig. 7 is a circuit schematic depicting an analog circuit which functions to electrically interface the optical detector of the structural information detector of Figure 6 with signal-processing electronics;

Fig. 8 is a circuit schematic depicting the current source circuit for light-emitting diodes of the optical sensor portion of the Figure 6 structural information detector;

Fig. 9 is a sectional view of one particular form of the Figure 6 structural information detector;

Fig. 10 is a perspective view of another particular form of the Figure 6 structural information detector in which the components are carried by a semiconductor substrate; and

Fig. 11 is a perspective view of an optical system usable in the Figure 6 structural information detector as well as in the structural moment detectors or flexural rigidity sensors of the prior art.

As used herein, the term "structural moment detector" means a device which measures the integral of the structure moment between two points on a structure. Such devices are known in the art, but, for clarity, a typical structural moment detector will be briefly described with reference to Figs. 1-3 and the accompanying descriptive material.

The structural moment detector shown in Figure 1 is basically an autocollimator that is insensitive to linear dynamic motions but responds to angular deflection of one end of the sensor with respect to the other. The structural moment detector illustrated

consists of two separate parts which are mounted at spaced locations on a beam 10. One of the parts 11 is a support bracket 12 which carries a light-emitting diode (LED) 13, a collimating lens 14 and dual photovoltaic detectors 15. The other part 16 of the structural moment detector consists of a support bracket 17 which carries a plane front mirror 18. The two parts 11 and 16 are suitably joined by a bellows or other hood member (omitted for clarity of illustration) to exclude extraneous light. The LED 13 emits an infrared light beam 19 which is collimated by the collimating lens 14. The collimated light beam 19a impinges on the mirror 18 and, as indicated by the dashed lines 10, is reflected back through the collimating lens 14 to the photovoltaic cells 15. Angular motions, but not linear motions, of the mirror 18 result in varying amounts of infrared radiation reaching each of the photovoltaic cells 15. The difference in voltage output of the photovoltaic cells 15 is then proportional to the angular motion of the mirror 18 with respect to the cells 15.

Structural moment detectors of the Figure 1 form are capable of measuring the deflection of the beam with a resolution of 1 milliarc second (4.85×10^{-9} radians) with a range of ± 6 arc seconds. Where such accuracy is not required, such devices can be fabricated which have a resolution of at least 1 arc second with a dynamic range of $\pm 3^{o}$. Such devices are capable of operating from DC to 50 MHz, the upper limit being established by the frequency limitation of the

photovoltaic cells.

Typical circuits which are used in conjunction with the mechanical components of the structural moment detector of Fig. 1 are illustrated in Figs. 2 and 3. Fig. 2 is a schematic diagram of a suitable LED driver circuit which is a simple constant current source circuit which is required to provide a light source with constant light intensity. A typical suitable readout circuit is illustrated in Fig. 3, which depicts an analog output circuit consisting of a first stage amplifier with common mode rejection that permits linear operation of the photovoltaic cells.

The operation of the structural moment detector can be illustrated by reference to a simplified example of a cantilevered beam which is loaded and the structural moment detector is mounted at points a and b located near the supported end of the cantilevered beam. If the deflection of the beam is measured as θ, the angle between surface tangents at points a and b, the output voltage of the photovoltaic cells is proportional to this angle, and according to the Area Moment Theorem

$$V_{out} \propto = \frac{\int_a^b M dx}{EI} = \frac{1}{EI} \int_a^b M dx$$

where

M is the applied moment between points a and b

E is the modulus of elasticity

I is the moment of inertia

θ is the angular difference between surface tangents at points a and b

x is the linear surface distance between points a and b.

If a load P is placed on the end of a beam of length L and is the distance between points a and b,

then

$$V_{out} \propto \theta = \frac{1}{EI} \frac{PL\delta}{2}$$

To illustrate the sensitivity of the structural moment detector, a load of 1 gram was placed at the end of an 8" cantilevered beam. The device was mounted near the support of the beam such that points a and b were 1.5" apart. With this load

$$V_{out} = 30 \text{ millivolts}$$

and

$$\theta = 1.3 \times 10^{-7} \text{ radians.}$$

Since it is impossible to load a structure without changing the total moment which occurs between two points on the structure, it is possible to use the structural moment detector as an extremely accurate and extremely sensitive sensor having a range which far exceeds that of conventional sensors of the prior art.

Illustrated in Fig. 4 is a monitoring system employing structural moment detectors. As shown in Fig. 4, the structural behaviour 41, which is effected by the forces acting on a structure, are sensed by an array 42 of structural moment detectors (SMD's), located on the structure. The SMD's 42 are located on the structure so as to provide primary electronic signals 43 which are proportional to the structural behaviour parameter of interest. The primary electronic signals 43 from the SMD array 42 are fed to signal processing and buffering equipment 44, which includes electronic circuitry which modifies the information content of the primary signals 43 (e.g., rejection of background noise, rejection of signal components induced by other forces, etc.) and which electrically isolate the

sensors from the remainder of the system. The processed signals 45 are then transmitted to analog-to-digital converters 46 which convert the analog information in the processed signals 45 to a digital format compatible with various digital processors, recorders, editors and/or display units. The digital signals 47 are then transmitted to a data processor 48 which will usually be a single-frame computer which is capable of accepting digital data and manipulating it in a predetermined programmable fashion, in order to convert the digitized measurement information into a digital representation of the desired system data. The digital representation data 49 is optionally transmitted to data recording/editing equipment 50 which may provide for permanent recording of all or part of the acquired data for later use and which may, additionally, provide manual editing capability. The recorded and/or edited data 51 may optionally be transmitted to data display equipment 52 which provides visual display of the acquired data and, additionally, may provide for the predetermined alteration of the means by which the data processing equipment 48 is transforming acquired data or the manner in which data is digitized, recorded, edited and/or displayed. Feedback loops 53 may be optionally provided, through which the information at one stage is fed backwardly and/or forwardly to another stage of the system to provide improved accuracy, estimation, prediction or other similar functions. These feedback paths may be electrical, optical, mechanical and/or may involve human interpretations and adjustments.

According to this invention, structural moment detectors are used for geophysical exploration, these detectors being incorporated into systems, similar to that of Figure 4 for making geophysical measurements.

The use of such systems makes it possible to provide the geophysical exploration community with a significantly improved seismic instrumentation system; the improvement resulting not only from the provision of a sensor which provides better seismic information but also from improvements which due to the use of SMD technology, become possible in the data processing software. The existing geophysical models used in seismic data processing and other portions of the existing data processing techniques have evolved over a period of time and are the direct result of theoretical and empirical investigations. The seismic sensors with their varied characteristics have had direct impact on data processing construction. The seismological instrumentation system provided by the present invention gives the capabilities promised by "high resolution seismology".

A seismometer built around an SMD system has a greater reliability (no moving parts), a greater signal to noise ratio and provides measurement capabilities not found in conventional sensors.

As an example, a SMD system was taken to a well location which was to be fractured. It was mounted on a surface outcropping of rock by epoxying the sensor to the rock. This was to minimize the effects of horizontal, man-created disturbances (such as the pump trucks) while providing a clear indication of seismic information generated at depth. In fact, the system was not greatly affected by surface disturbances, and the output became saturated at the same time the fracture occurred (allowing for transmission time). This experiment provided a clear indication that it is possible to selectively detect seismic disturbances depending on the exact manner in which that disturbance affects the structure to which the SMD is mounted.

As another embodiment a structural mount is provided

that is sensitive to the shear wave rather than the compression wave. This allows the construction of a downhole instrumentation system to provide an output proportional to the shear wave velocity at the location of the sensor which, in turn, is a direct function of the porosity of the medium.

In order to obtain a measurement for use in a "high resolution" seismological instrumentation system that provides a significant increase in capability over current technologies, seismological sensors embodying the present invention can be made primarily sensitive to seismic information generated at depth and quite insensitive to seismic information that is transmitted along the surface. This is in contrast to conventional sensors that sense acceleration regardless of the source. This selective sensitivity is possibly by using SMDs applied to an anisotropic structure where the stiffness of the structure in two directions can be made extremely high while the stiffness in the measurement direction can be made quite low. This allows alignment of the sensor to the directions from which the information is caught while rejecting other information and permit separation of pressure and shear waves.

Geophysical measurement systems constructed in accordance with the present invention are generally similar to conventional systems which provide geophones, with the exception that the geophones are replaced by appropriately mounted SMD sensors 221, sensitive to the appropriate directions, as shown in Fig. 5A. The signal processing electronics and data processing equipment, recording equipment, software and displays required to produce the desired seismic information from the SMD signals is contained in an instrument truck 222, a typical output chart trace being shown in Figure 5B.

The SMD sensors used in Figures 4 and 5 are structural moment detectors (SMD's), for example, of the prior art form shown in Figure 1. These sensors can alternatively be implemented by means of "structural information detectors" in which raw data from a structural moment detector is converted and processed within a unitary device (including the SMD) such that the signal output from the device has a directly useful information content.

Fig. 6 is a block diagram illustrating the major sub-components of a structural information detector suitable for use in the systems described hereinbefore. The structural information detector, generally indicated by the reference numeral 410, is depicted for purposes of illustration as being mounted upon a simple cantilevered beam 411 and consists of a housing 412, an optical sensor 413, sensor power supply 414, raw signal conversion circuitry 414c and signal-processing electronics, including a microprocessor and appropriate software 415. The optical sensor 413, for example, a structural moment detector of the type generally disclosed in U.S. patent 4,287,511 (sometimes also known as a "flexural rigidity sensor") measures, as indicated by the dashed line 413a, the relative orientation of surface coordinate vectors which are, as illustratively depicted in Fig. 6, normals 416 to the surface 411a of the beam 411. If a force F (417) is applied in the direction of the arrow 417a to the beam 411, resultant bending of the beam 411 will cause a change in the relative orientation of the surface coordinate vectors 416 to the positions indicated by the dashed lines 416a, i.e., from the angular orientation 418 $\theta 1$ (shown in Fig. 6, illustratively, as 180°) to an angular orientation 418a $\theta 2$ which (as illustratively depicted in Fig. 6)

is greater than θ1. Power 419 from an external power source 419a is supplied to the circuitry 414 which, as explained below, provides a regulated power supply 414a to the optical sensor 413. The raw data 413b from the optical sensor 413, which could be a variable voltage or a variable current, is supplied to the raw signal conversion portion of the circuitry 414, which converts the raw data, as will be further explained below, to a form which is the input 414b to the signal and data-processing electronics and software 415, which processes the converted signal 414b and provides, as the output 415a of the structural information detector 410, a signal which embodies useful sturctural information 420 which directly indicates the effect of the force F acting on the beam 411. As indicated by the line 420a, the useful structural information 420 can be utilised in any or all of a variety of ways, i.e., it can be used as the input to a direct display 420b which may be a simple galvanometric meter, liquid crystal display, light emitting diode display, cathode ray tube or the like. Also or alternatively, the useful structural information 420 can be used as the input to a semi-permanent or permanent recording device 420c, such as a paper recorder, magnetic recorder, semiconductor storage device, bubble memory storage device, or holographic storage device. Also or alternatively, the useful structural information 420 can form the input to various control devices 420d such as servomotors and other similar electromechanical devices.

The raw data output 413b of the optical sensor 413 is (referring to Fig. 7) the input to the signal processing electronics, including computational software therein depicted. The function of the circuitry depicted in Fig. 7 is to convert the raw data input 413b from the optical sensor into data suitable for electronic data processing and then to perform the data-processing

function to yield a signal, the components of which directly provide useful structural information. According to the presently preferred embodiment of the structural information detector, the conversion is performed with analog electronics, rather than digital. The analog electronics perform two distinct functions. First, the output signal 413b from the optical sensor is measured and converted to a proportional voltage in a voltage follower circuit which, for clarity of illustration, are those components which are located within the dashed line 421. The second function is to amplify the proportional voltage signal from the voltage follower circuit 421 by feeding it through a gain control 422 into an amplifier which, for purposes of clarity of description, are those components located within the dashed line 423. The voltage follower circuit 421 operates as a short circuit load for the photovoltaic cells of the optical sensor. Feedback is added in the amplifier circuit 423 to shape the upper end of the frequency response so that spurious high frequency noise is attenuated. This function is performed by applying the output of IC1 (pin 7) to the input (pin 6) of IC2 through a voltage divider formed by R7-R8. IC2 acts as a low-pass filter. The output of IC2 (pin 7) is fed back through R16 to the input 3 of IC1 to act as an automatic bias adjustment. An offset voltage adjustment is provided to remove any bias due to photocell mismatch.

The gain control 422 provides a means of balancing the mechanical gain of different sensors and compensating for components variation. The nominal adjustment range is $\pm 15\%$. The amplifier 423 is a high gain direct-coupled amplifier with feedback to further attenuate high frequency noise levels. Nominal gain is 1.5 volts/microamp and the bandwidth is normally initially set at 50-500 Hz. In essence, A2 is a variable cut-off

low-pass filter. If the DC case is considered, its output will seek a level such that the voltage presented to pin 3 of A1 is equal to that presented to pin 2 by the voltage follower circuit. The scaling of the system is such that

$$U_{null} = V_{int}\ (R17/R16+R17) = V_{in}$$

where V_{int} is the integrator output, V_{in} is the first stage and U_{null} is the input to A1, pin 2. Thus, for low frequency, V_{int} represents a scaled value equal to or greater than V_{in} independent of the gain in the second stage of the amplifier. The implication of this is that the gain of the second stage can be set very high for frequencies above the autonumm roll-off without completely losing DC information.

Support and bias circuits which include the components which are, for clarity of illustration, enclosed within the dashed line 424 are provided to provide conditioned power and bias voltages for the components of the voltage follower 421 and amplifier 423.

The output 426 of the amplifier 423 is an analog signal which is converted to a digital signal in the A-D converter 422a. A non-limiting, illustrative, exmaple of a suitable analog-digital converter is manufactured by the U.S. firm Analog Devices under number HAS1202.

The signal-processing electronics also includes a microprocessor 425 and appropriate computational software which converts the output signal 422b of the A-D converter 422a into electrical signals 420 which directly provide data related to the effect of the force acting on the structure to which the structural information detector is attached. In the presently preferred embodiment, this component

includes a microprocessor, the necessary supporting devices and a power supply, details of which are omitted for purposes of clarity because they are well-known to those skilled in the art. Suitable non-limiting examples of microprocessors which can be employed are the TI9000 or the Intel 8086.

All of the elements described in Figs. 7 and 8 may be fabricated on a printed circuit board using standard integrated circuits or on a single thick film substrate where the circuits have been wire bonded to the substrate. In the embodiment of the detector described in connection with Fig. 10, these components may be made as a single integrated circuit on the same semiconductor substrate chip used in fabricating the optical sensor.

Another function of the signal-processing electronics is to provide a precise current to the light emitting diode of the optical sensor.

Typical non-limiting, illustrative, values of the components of Fig. 7 are set forth below:

<u>Voltage Follower/Amplifier</u>

R1 - 220K
R5 - 1K
R6 - 2.2K
R9 - 2.2M
R23 - 82
A1 - Operational Amplifier LF353/2

<u>Second Stage Amplifier</u>

R2 - 680K
R3 - 10K
R4 - 1M
R7 - 100K
R8 - 10K

R13 - 2.2M
R15 - 220K
R16 - 10K
R17 - 1K
C2 - 47PF
C3 - 10MF
C4 - 5PF
A1 - Operational Amplifier LF 353/2
A2 - Operational Amplifier LF 353/2

Support and Bias Circuits

R10 - 100K
R11 - 1.8K
R12 - 100K
R14 - 1.8K
C5 - 10MF
C6 - 10MF
C7 - 10MF
C8 - 10MF
Z1 - LM336
Z2 - LM336

For the sake of clarity, the power supply circuitry has been separated from the circuitry of Fig.7 and is shown schematically in Fig. 8. The 15 volt power supply 431 is provided by the support and bias circuitry 424 of Fig. 7.

The power supply circuitry of Fig. 8 utilises two amplifiers in a high gain feedback arrangement to provide the necessary precise current 432 to the light emitting diode.

Typical non-limiting, illustrative, values of the components of Fig. 8 are set forth below:

Power Supply

R18 - 3.3K
R19 - 10K
R20 - 10K
R21 - 10K
R22 - 47
C9 - 10MF
C10 - 10MF
IC3 - Operational Amplifier LF353/2
Q1 - 2N5457
Q2 - TIP21

Fig. 9 is a sectional view illustrating a particular form of structural information detector which consists of a first housing sub-assembly generally indicated by reference character 440 containing the sensor power supply/raw signal conversion/ signal-processing electronics 441 of Figs. 7 and 8, a light emitting diode 442, a pair of photovoltaic detectors 443 and a collimating lens 444 carried proximate the open end of a barrel portion 445 formed in the housing 440. A second housing sub-assembly, generally indicated by reference numeral 446, carries a plane surface mirror 447 on the inner end 448 of a mating barrel portion 449 formed in the housing sub-assembly 446. Although a substantial clearance 450 is shown between the barrel portion 445 formed in the first housing sub-assembly 40 and the barrel portion 449 formed in the second housing sub-assembly 446, it will be understood by those skilled in the art that this clearance is shown only for the purpose of clarifying the mechanical relationship of the two housing sub-assemblies 440 and 446. In actuality, the mating barrel portion 449 formed in the second housing sub-assembly 446 is shaped and dimensioned to receive the barrel portion 445 formed in the first housing sub-assembly 440 with an interference